EPA/600/R-02/066
September 2002

High Energy Electron Injection (E-Beam) Technology for the *Ex-Situ* Treatment of MtBE-Contaminated Groundwater

Innovative Technology Evaluation Report

By

Tetra Tech EM Inc.
San Diego, California 92101

EPA Contract No. 68-C-00-181
Task Order No. 15

Work Assignment Manager

Albert D. Venosa
Land Remediation and Pollution Control Division
National Risk Management Research Laboratory
Cincinnati, Ohio 45268

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

NOTICE

The information in this document has been funded by the U.S. Environmental Protection Agency (EPA) under Contract No. 68-C-00-181 to Tetra Tech EM Inc. It has been subjected to the Agency's peer and administrative reviews and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement of recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

ABSTRACT

This Innovative Technology Evaluation Report documents the results of a demonstration of the high-energy electron injection (E-Beam) technology in application to groundwater contaminated with methyl t-butyl ether (MtBE) and with benzene, toluene, ethylbenzene, and xylenes (BTEX). The E-beam technology destroys organic contaminants in groundwater through irradiation with a beam of high-energy electrons. The demonstration was conducted at the Naval Base Ventura County (NBVC) in Port Hueneme, California.

Results of two weeks of steady state operation at an E-beam dose of 1,200 kilorads (krads) indicated that MtBE and BTEX concentrations in the effluent were reduced by greater than 99.9 percent from influent concentrations that averaged over 1,700 μg/L MtBE and 2,800 μg/L BTEX. Further, the treatment goals for the demonstration, which were based on drinking water regulatory criteria, were met for all contaminants except for *t*-butyl alcohol (tBA), a degradation product of MtBE. Dose experiments indicated that tBA was not consistently reduced to below the treatment goal of 12 μg/L although the results indicated that tBA by-product formation decreased as dose increased. Thus, it is possible that, at increased energy input beyond that tested in the demonstration, the E-Beam technology might have met the prescribed treatment objectives for TBA. Acetone and formaldehyde were the two most prevalent organic by-products that were formed by E-beam treatment, with mean effluent concentrations during the two-week steady state testing of 160 and 125 μg/L, respectively. Bromate was not formed during E-beam treatment.

An economic analysis of the E-beam treatment system indicated that the primary costs are for the E-beam equipment and for electrical energy. The estimated cost ranged from over $40 per 1000 gallons for a small-scale remedial application to about $1.00 per 1000 gallons for a larger-scale drinking water application.

TABLE OF CONTENTS

TABLES

FIGURES

ACRONYMS AND ABBREVIATIONS

ACL	Alternate concentration limits
AEA	Atomic Energy Act
AL	Action level
ARAR	Applicable or relevant and appropriate requirement
BTEX	Benzene, toluene, ethylbenzene, and xylenes
CAA	Clean Air Act
CERCLA	Comprehensive Emergency Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
Cl^-	Chloride ion
CO_2	Carbon dioxide
COD	Chemical oxygen command
CWA	Clean Water Act
DBPR	Disinfection By-product Rule
1,2-DCE	1,2-Dichloroethene
DHS	Department of Health Services
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DOE	Department of Energy
e^-_{aq}	Aqueous electrons
E-Beam	High energy electron injection
EPA	U.S. Environmental Protection Agency
gpm	Gallons per minute
HAA	Haloacetic acid
HVEA	High Voltage Environmental Applications, Inc.
H_2	Hydrogen
H_2O_2	Hydrogen peroxide
•H	Hydrogen atom
H_3O^+	Hydronium ion
ICAL	Initial calibration
ITER	Innovative Technology Evaluation Report
Krads	Kilorads
kV	Kilovolts
kW	Kilowatts
kWh	Kilowatt hours
LCS/LCSD	Laboratory control samples and laboratory control sample duplicates
LDR	Land Disposal Restriction
mA	Milliamps
MCL/MCLG	Maximum Contaminant Level and Maximum Contaminant Level Goal
MDL	Method detection limit
µg/L	Micrograms per liter
mg/L	Milligrams per liter
mm	Millimeters
MS/MSD	Matrix spike/matrix spike duplicate
MtBE	Methyl-t-butyl ether
NAAQS	National Ambient Air Quality Standards

ACRONYMS AND ABBREVIATIONS (Continued)

NBVC	Naval Base Ventura County
NDMA	N-nitrosodimethylamine
NESHAP	National Emission Standards for Hazardous Air Pollutants
NEX	Naval Exchange
NFESC	Naval Facilities Engineering Service Center
NOEL	No observable effect level
NPDES	National Pollutant Discharge Elimination System
NRMRL	National Risk Management Research Laboratory
NSPS	New Source Performance Standards
•OH	Hydroxyl radical
OSWER	Office of Solid Waste and Emergency Response
PAH	Polynuclear aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PCE	Tetrachloroethene
POTW	Publicly owned treatment works
PPE	Personal protection equipment
ppm	Parts per million
PVC	Polyvinyl chloride
QA	Quality assurance
QAPP	Quality assurance project plan
QC	Quality Control
QCC	Quality Control Coordinator
RCRA	Resource Conservation and Recovery Act
RRF	Relative response factor
RPD	Relative percent difference
RSD	Relative standard deviation
RTD	Resistance temperature device
SDS	Simulated distribution system
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SVOC	Semi-volatile organic compound
tBA	t-Butyl alcohol
TCE	Trichloroethene
TEP	Technology evaluation plan
TOC	Total organic carbon
TSCA	Toxic Substances Control Act
TTHM	Total trihalomethanes
TSA	Technical systems audit
UCL	Upper confidence limit
UFC	Uniform formation conditions
VOA	Volatile organic analysis
VOC	Volatile organic compound
WQS	Water quality standard

EXECUTIVE SUMMARY

The high-energy electron injection (E-Beam) technology destroys organic contaminants in groundwater through irradiation with a beam of high-energy electrons. The injection of accelerated electrons into an aqueous solution results in the formation of three primary reactive species: aqueous electrons (e^-_{aq}) and hydrogen radicals (•H), which are strong reducing species; and hydroxyl radicals (•OH), which are strong oxidizing species. These reactive species can destroy most organic compounds to non-detectable concentrations. However, oxidation by-products such as acetone, aldehydes, and glyoxals, may be formed in significant concentrations.

The capabilities of the E-Beam technology for treating groundwater contaminated with methyl *t*-butyl ether (MtBE) and with benzene, toluene, ethylbenzene, and xylenes (BTEX) was demonstrated by Haley and Aldrich in the summer and fall of 2001. The site that was selected for the demonstration was the source zone of the Naval Exchange Gasoline Station site at the Naval Base Ventura County in Port Hueneme, California. Treatment goals were established for the demonstration based primarily on California maximum contaminant levels (MCL) for drinking water.

The demonstration of the E-Beam technology was implemented in two phases, including a two-week steady-state operation at an E-beam dose of 1,200 kilorads (krad) and a shorter series of tests in which the E-Beam dose was varied from 800 to 1,600 krad. During the demonstration, grab samples of the groundwater were collected before and after treatment at the E-Beam influent and effluent sampling locations and analyzed for volatile organic compounds (VOC), aldehydes/glyoxals, bromate, and general water quality variables.

Results of the two-week steady-state operation indicated that MtBE and BTEX concentrations in the effluent were reduced by greater than 99.9 percent from influent concentrations that averaged over 1,700 µg/L MtBE and 2,800 µg/L BTEX. Further, the 95 percent upper confidence level for the mean effluent concentrations of MtBE, benzene, and toluene were below the corresponding treatment goals of 5 µg/L, 1 µg/L, and 150 µg/L, respectively; neither ethylbenzene nor xylenes were detected in the effluent. However, effluent concentrations of *t*-butyl alcohol (tBA), a degradation product of MtBE, were consistently several times the treatment goal of 12 µg/L.

Results of the dose experiments indicated that a dose of 800 krads was not quite sufficient to bring the concentration of MtBE to below the treatment goal of 5.0 µg/L, but higher doses were effective in meeting this treatment goal. However, tBA was not consistently reduced to below the treatment goal of 12 µg/L even at the highest dose (1,600 krads), although the results from the dose-response experiment indicated that tBA by-product formation decreased as dose increased. Thus, it is possible that, at increased energy input beyond that tested in the demonstration, the E-Beam technology might have met the prescribed treatment objectives for TBA.

A number of organic by-products were measured in effluent samples, including acetone, acetaldehyde, formaldehyde, glyoxal, and methyl glyoxal. Acetone and formaldehyde were the two most prevalent organic by-products, with mean effluent concentrations during the two-week steady-state testing of 160 and 125 µg/L, respectively. Bromate concentrations were near the

detection limit of 1 μg/L in both influent and effluent samples; therefore, bromate does not appear to be a by-product of E-beam treatment.

An economic analysis of the E-beam treatment system was conducted for two applications: a groundwater remedial application at a flow rate of 10 gallons per minute, and a larger-scale drinking water treatment application at a flow rate of 10 million gallons per day. The primary costs in both applications were for the E-beam equipment and for electrical energy. For the remedial application, the overall cost was estimated to be over $40 per 1000 gallons, while for the larger-scale drinking water application the overall cost was estimated to be about $1.00 per 1000 gallons. The lower unit cost for the larger-scale drinking water application resulted from economies of scale and the assumption that much lower influent concentrations of MtBE would be treated in such an application.